Advancing energy transition with waste heat recovery

The use of waste heat recovery (WHR) systems in cement plants can provide cement producers with cheaper energy as well as a more sustainable way of producing cement.

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Cement manufacturing is one of the most energy-intensive industrial processes and remains a major contributor to global CO_2 emissions. Despite significant technological advancements, the sector continues to rank as the third-largest industrial energy consumer worldwide. Additionally, cement production is responsible for the second-largest share of direct industrial CO_2 emissions globally (IEA, Technology Roadmap-Low Carbon Transition in the Cement Industry, 2018).

The European cement industry is aware of its environmental footprint and has already made substantial strides in reducing emissions. Since 1990 CO_2 emissions from cement manufacturing have decreased by 15 per cent. This progress is part of a broader commitment to sustainability, with the industry implementing a wide range of technologies and innovation projects. CEMBUREAU, the European cement association, has identified in its Net Zero Roadmap the sector's ambitious climate goals for the coming decades, with the key milestones of achieving a 37 per cent reduction in CO_2 emissions from cement production and a 50 per cent reduction across the entire value chain by 2030. The roadmap targets carbon neutrality in cement production in Europe, with the potential extended across the whole value chain by 2050.

To continue this path and achieve these goals the cement industry is exploring a variety of carbon mitigation solutions, including the use of alternative fuels (less carbon-intensive), reducing the clinker-to-cement ratio and integrating energy efficiency and carbon capture technologies into the production process.

Waste heat recovery for carbon neutral energy transition

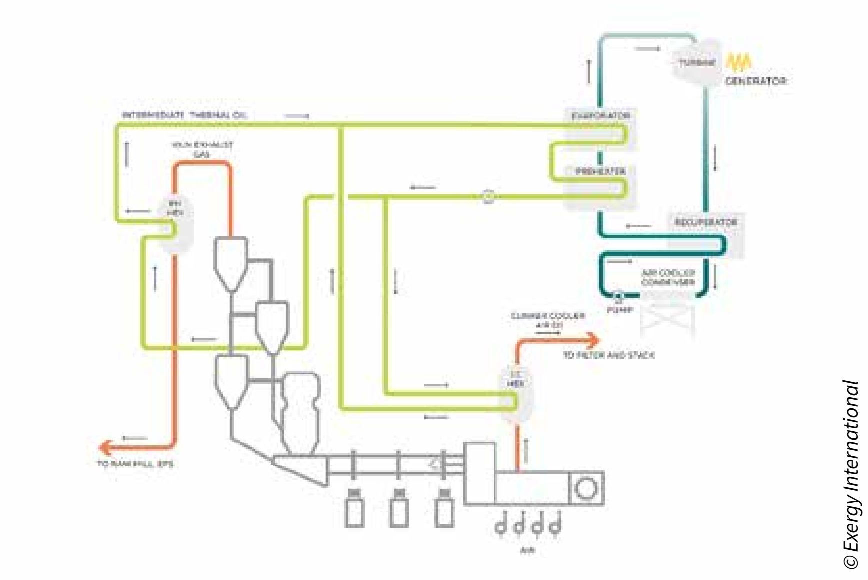
The adoption of waste heat recovery (WHR) technology is becoming increasingly essential. WHR is widely applied in a range of industries, including cement production, to reduce their reliance on fossil fuels and mitigate CO_2 emissions associated with electricity generation. According to a recent market report by Global Market Insight (2024), the market of cement WHR systems was valued at US$15.2bn in 2023 and is projected to grow at a CAGR of 7.8 per cent from 2024 to 2032, reaching US$28.8bn with a total capacity of 7.5GWe by the end of this period.

Figure 1: a 2MWe Radial Outflow Turbine in Exergy's workshop – its radial configuration allows for higher efficiency

WHR systems capture and convert waste heat from cement manufacturing – typically from exhaust gases of the clinker cooler and kiln preheater – into usable energy, which significantly enhances the energy efficiency of cement operations. These systems not only lower emissions but also reduce energy costs by generating electricity from otherwise wasted heat, making them a critical component in the move toward more sustainable industrial practices.

Organic Rankine cycle (ORC) technology is particularly suited for waste heat recovery from low- to medium-temperature heat sources, ranging between 90-500˚C, and is designed to convert waste heat into electrical power. In this temperature range, ORC WHR plants offer several advantages compared to the traditional Rankine cycle. Instead of water, the ORC uses organic fluids such as hydrocarbons or refrigerants, which are chosen based on their compatibility with the heat source. This approach results in higher cycle and turbine efficiency, even in off-design conditions. Additionally, the use of organic fluid eliminates the risk of turbine blade erosion, typically occurring with steam cycles, thanks to dry expansion. The ORC cycle is simpler to operate and more flexible, requiring fewer personnel on-site as the plant can be largely automated and remotely controlled. In terms of sustainability, ORC plants allow no water consumption, when coupled with an air-cooled condenser. This possibility is extremely advantageous for installation in remote sites where water

Figure 2: example of an ORC WHR cycle in a cement plant



availability is limited. Finally, ORC systems have lower operational costs and require less maintenance compared to steam-based solutions.

Exergy's ORC solutions with advanced ROT technology

Exergy International has taken the ORC technology a step further by introducing the Radial Outflow Turbine (ROT) in 2010. The ROT offers several advantages over traditional axial or radial inflow turbines used in the ORC market. Its radial configuration allows for higher efficiency, and up to nine stages on a single disk, which reduces the length of the turbine. Its patented mechanical group minimises tip leakage and friction losses and allows rapid maintenance. The ROT's straight blades' design also reduces 3D effects and turbulence, thus enhancing reliability. Moreover, the ROT technology enables a direct coupling with the generator, which reduces vibrations and extends the plant's lifespan. Maintenance is simpler and more cost-effective, as key components can be removed without draining the organic fluid, significantly reducing plant downtime.

Since its introduction, Exergy has designed and installed over 50 ORC plants with ROT technology, totalling more than 550MWe of capacity. Exergy's ORC systems can be installed in cement plants of any size, in a range between 1-20MWe output, also in modular configuration for a maximum of total installed power of 50MWe.

How ORC WHR systems work

ORC WHR systems in the cement industry are typically configured with an indirect heat exchange system that utilises an intermediate loop, which circulates a heat transfer fluid (HTF) such as thermal oil, pressurised water or saturated steam. The system captures thermal energy from the exhaust gases in the preheater and clinker cooler, transferring this heat to the ORC module through a thermal oil loop. Inside the ORC closed circuit, the organic fluid, initially in liquid form, is pressurised by a pump before being heated and evaporated in the preheater and evaporator, respectively, using heat from the HTF. The resulting vapour is then expanded in a turbine to generate electricity. Following expansion, the exhaust vapour is cooled and condensed in the regenerator and condensing system before the cycle is repeated.

The design of the heat exchanger for the heat transfer in the clinker cooler and preheater is crucial and needs to be tailored to the specific technical features and processes of the cement plant, involving a careful consideration of dust type and concentration, gas velocity, thermal oil operating pressure and velocity, and the use of a dedicated cleaning system.

The design of the ORC plant includes selection of the most appropriate working fluid, fitting the heat source characteristics (typically cyclopentane, although over 12 different types of fluids have been used in cement application) and the configuration of the equipment.

This includes:

- **preheater and evaporator** – to extract the heat from the intermediate thermal fluid. Shell and tube heat exchangers are usually applied, but they can vary in geometry and configuration depending on the heat characteristics and the total thermal input
- **superheater** – added in some cases to heat up the working fluid vapour coming out from the evaporator before before entering the turbine. This increases power generation from the turbine.

Figure 3: an Exergy ORC installation at a cement plant in Italy

- **turbine** – the key component of the plant, producing mechanical energy that is converted into electricity by a generator directly coupled with the turbine shaft
- **condenser** – cools the organic fluid, bringing it back to liquid before entering the pump. To avoid water consumption and promote sustainability, an air-cooled condenser (ACC) is typically preferred. However, if a stable water supply is available, a water-cooled condenser (WCC) may also be employed.
- **feed pump** – brings the organic fluid from the condensation pressure to the maximum pressure of the cycle.

The ORC system is integrated into the cement plant as a stand-alone unit, offering the benefit of not impacting normal operations or production capacity during installation, operation or maintenance.

Investment

The typical payback period for an ORC WHR system in a cement plant ranges between 4-8 years, though this can vary based on several factors, including the required electrical output of the ORC, the specific configuration of the cement plant and the prevailing electricity selling prices.

Other factors include the cost of installation, operational efficiency and maintenance costs. In countries where government incentives are available, such as carbon credits, green certificates and premiums for reduced CO_2 emissions, the payback period can be significantly reduced. These incentives not only enhance the economic viability of the ORC WHR system but also align with broader sustainability goals, which further improves the financial attractiveness of such investments.

Additionally, factors such as energy price volatility, local regulations and the plant's operational load can also impact the return on investment, making ORC WHR systems an increasingly attractive option for cement plants.

Case study – Greece

Exergy has installed several WHR plants in the industrial sector, featuring 11 total installations worldwide. One of the solutions that Exergy recently studied for a cement application in Greece is a 10MWe unit that efficiently recovers exhaust gases from both the preheater and the clinker cooler of two kiln lines.

By harnessing preheater exhaust gases at a temperature of 386˚C with a flow rate of 162,577Nm^3/h, along with clinker cooler exhaust air at 332˚C and a flow rate of 102,625Nm^3/h, this system can generate around 10MWe with an ORC efficiency of 25 per cent. The solution, designed by Exergy, features an air-cooled condensing system and is equipped with Exergy's Radial Outflow turbine technology. Tables 1 and 2 provide further technical details about the heat source conditions.

Under the specified conditions, the expected performances of Exergy's ORC EPS 1100 unit at the cement plant are as shown in Table 3.

Conclusion

In conclusion, advanced WHR technologies play a pivotal role in achieving carbon neutrality in the cement industry, offering numerous advantages:

- Enhancing process energy efficiency by maximising the use of available heat sources and repurposing thermal losses within a circular model.
- Reducing the demand for conventional fossil fuel energy by employing clean electricity generated on-site through the ORC.
- Facilitating access to electricity via independent microgrids for remote or isolated sites.
- Lowering energy costs, thereby increasing overall profitability.
- Being less susceptible to energy price volatility.
- Reducing Scope 2 carbon emissions by utilising a clean electricity supply.
- Improving companies' sustainability credentials, making them more competitive in the market.

Continued innovation and strategic deployment of WHR systems are essential for accelerating the transition towards a more sustainable cement sector. ■

Table 1: hot source and oil nominal conditions from Kiln Line 1

	Clinker cooler	Preheater tower
Exhaust gas flow rate (Nm^3/h)	102,625	162,577
Exhaust gas temperature at boiler inlet (˚C)	332	386
Exhaust gas temperature at boiler outlet (˚C)	100	190
Recovered heat from exhaust gases (kW_{th})	8670	13,333
Thermal oil flow rate (kg/s)	18.4	31.3
Thermal oil temperature at boiler inlet (˚C)	85	130
Thermal oil temperature at boiler outlet (˚C)	301.1	316.2

Table 2: hot source and oil nominal conditions from Kiln Line 2

	Clinker cooler	Preheater tower
Exhaust gas flow rate (Nm^3/h)	134,771	160,047
Exhaust gas temperature at boiler inlet (˚C)	306	359
Exhaust gas temperature at boiler outlet (˚C)	100	190
Recovered heat from exhaust gases (kW_{th})	10,085	11,262
Thermal oil flow rate (kg/s)	24.3	29.7
Thermal oil temperature at boiler inlet (˚C)	85	130
Thermal oil temperature at boiler outlet (˚C)	279.3	298.5

Table 3: Exergy ORC performance

	Preheater tower
Recovered heat by thermal oil from exhaust gas (kW_{th})	43,350
Gross ORC Power (kW_e)	10,835
Net Power (kW_e)	9875
ORC Gross efficiency (%)	25
WHR availability (%)	96